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Determination of growth-stage-specific crop coefficients (Kc) of cotton and wheat

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ABSTRACT

Development of crop coefficient (Kc), the ratio of crop evapotranspiration (ETc) to reference evapotranspiration (ETo), can enhance ETc estimates in relation to specific crop phenological development. This research was conducted to determine growth-stage-specific Kc and crop water use for cotton (*Gossypium hirsutum*) and wheat (*Triticum aestivum*) at the Texas AgriLife Research field at Uvalde, TX, USA from 2005 to 2008. Weighing lysimeters were used to measure crop water use and local weather data were used to determine the reference evapotranspiration (ETo). Seven lysimeters, weighing about 14 Mg, consisted of undisturbed 1.5 m $\times$ 2.0 m $\times$ 2.2 m deep soil monoliths. Six lysimeters were located in the center of a 1-ha field beneath a linear-move sprinkler system equipped with low energy precision application (LEPA) and a seventh lysimeter was established to measure reference grass ETo. Crop water requirements, Kc determination, and comparison to existing FAO Kc values were determined over a 2-year period on cotton and a 3-year period on wheat. Seasonal total amounts of crop water use ranged from 689 to 830 mm for cotton and from 483 to 505 mm for wheat. The Kc values determined over the growing seasons varied from 0.2 to 1.5 for cotton and 0.1 to 1.7 for wheat. Some of the values corresponded and some did not correspond to those from FAO-56 and from the Texas High Plains and elsewhere in other states. We assume that the development of regionally based and growth-stage-specific Kc helps in irrigation management and provides precise water applications for this region.

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1. Introduction

Determination of actual crop evapotranspiration (ETc) during the growing season has a potential advantage to attain proper irrigation scheduling. Crop coefficient (Kc) is widely used to estimate crop water use and to schedule irrigations. The concept of Kc was introduced by Jensen (1968) and further developed by the other researchers (Doorenbos and Pruitt, 1975, 1977; Burman et al., 1980a,b; Allen et al., 1998). The methodology was developed to provide growers with a simple ETc prediction tool for guiding irrigation management decisions. The use of on-site microclimatological data and crop coefficients enables the determination of crop water use and dissemination of such information to growers in a reliable, usable, and affordable format. Kc is defined as the following equation (Allen et al., 1998):

$$\mathrm{Kc} = \frac{\mathrm{ETc}}{\mathrm{ETo}} \tag{1}$$

This approach to ETc estimation is governed by empirically developed Kc ratios of measured ETc and reference evapotranspiration (ETo) which is based on either grass or alfalfa evapotranspiration. Values of Kc for most agricultural crops increase from a minimum value at planting until a maximum Kc is reached at about full canopy cover. The Kc tends to decline at a point after a full cover is reached in the crop season. The declination extent primarily depends on the particular crop growth characteristics (Jensen et al., 1990) and the irrigation management during the late season (Allen et al., 1998). A Kc curve is the seasonal distribution of Kc, often expressed as a smooth continuous function.

ETo has been standardized for grass or alfalfa (Jensen et al., 1990) and for a hypothetical short crop (Allen et al., 1998), and more recently developed for both a short crop (ETos) and a taller crop (*ETrs*) (Allen et al., 2005). ETo may be measured directly from a reference crop such as a perennial grass (Pruitt and Doorenbos, 1977; Watson and Burnett, 1995) or computed from weather data using (a) temperature models (Thornthwate, 1948; Doorenbos and

Abbreviations: ASCE, American Society of Civil Engineers; ETo, reference evapotranspiration; ETc, crop evapotranspiration; Kc, crop coefficient; Kco, crop coefficient based on the ASCE Penman–Monteith equation for grass; LEPA, low energy precision application.

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Pruitt, 1977), (b) radiation models (Doorenbos and Pruitt, 1977; Hargreaves and Samani, 1985), and (c) combination models (Allen et al., 1998). The Penman–Monteith (P–M) equation is adopted and recommended by FAO-56 (Allen et al., 1998) and by ASCE-EWRI (2005). The P–M can be applied to a variety of vegetation conditions, including systems having varying leaf area and varying height. It is possible to standardize parameters in the P–M equation including aerodynamic resistance for application to grass reference ETo (Allen et al., 1989, 1994, 1998; Jensen et al., 1990; ASCE-EWRI, 2005). ASCE adopted a standardized reference evapotranspiration equation to simplify and standardize the calculation (ASCE-EWRI, 2005). A key purpose of the ASCE/EWRI standardized ET equations is to utilize similar reproducible ETo values with routine weather data (Allen et al., 2005).

Weighing lysimeters are employed to measure ETo and ETc directly by detecting changes in the weight of the soil/crop unit (Howell et al., 1995a,b; Schneider et al., 1998; Marek et al., 2006). Weather data are used to compute ETo via equations such as the ASCE Penman–Monteith (ASCE-EWRI, 2005). By utilizing the following equation:

$$\mathrm{ETc} = \mathrm{Kc} \times \mathrm{ETo} \tag{2}$$

where all that is needed to provide growers with real time irrigation recommendations (ETc) are local weather stations to provide data to determine ETo. According to Allen et al. (1998), crop type, variety, and developmental stage affect ETc.

Potential evapotranspiration (PET) network is a group of meteorological stations to acquire weather data to compute PET and to disseminate it in an automated process providing timely, accurate data on ET for various crops (Howell, 1998). PET networks (Brock et al., 1995; Howell, 1998; Snyder, 1983) and crop simulation models (Guerra et al., 2005, 2007; Santos et al., 2000) have proven to be reliable, inexpensive, and effective tools for estimating crop water needs in research settings. The PET networks provide a 'uniform' and 'dependable' source of information on crop water use (Marek et al., 1996; Seymour et al., 1994). Recently, networks of weather stations have been established in many parts of Texas for the purpose of supporting predictions of crop ET. It is estimated that, in the northern Texas panhandle, yearly fuel cost savings would exceed 18 million dollars if all irrigators used the PET network data. However, to support predictions of crop evapotranspiration, generic crop coefficients will not fulfill the need for precise irrigation applications. The objective of this research was to determine crop water use (ETc) and develop crop coefficients (Kc) specific to multiple phenological stages for cotton and wheat grown in South Texas.

2. Materials and methods

2.1. Lysimeter facility

The lysimeter facility at the Texas AgriLife Research Center in Uvalde, Texas (29°13′N, 99°45′W; elevation 283 m), includes seven weighing (~14 Mg) lysimeters constructed between 2001 and 2006. Six lysimeters were established to measure crop evapotranspiration (ETc) and a seventh lysimeter was established to measure reference grass evapotranspiration (ETo). Construction details and resolution are described by Marek et al. (2006). Each lysimeter is 1.5 m × 2.0 m in surface area and 2.2 m deep. The surface area of the lysimeters accommodates the common row spacing utilized in the region. The soil monoliths of an Uvalde silty clay soil (fine-silty, mixed, hyperthermic Aridic Calciustolls with a pH of 8.1) in the lysimeters represent soils within an 80 km radius of the research center.

Microclimatological data were collected by a standard Campbell Scientific, Inc. (Logan, UT) weather station every 6 s with 15 min output. These include solar irradiance, wind speed, air temperature, relative humidity, precipitation, and barometric pressure (Dusek et al., 1987; Howell et al., 1995a,b). The mass of each lysimeter was sampled at a frequency of 1 Hz and averaged for every 5 min. Changes in lysimeter mass were measured as changes in load cell output from a platform scale (Avery Weigh Tronix scale model #: HSDS 6060, Fairmont, MN) in mV V^{-1} beneath each lysimeter and the lysimeter mass calibration. The calibration of the scale output (mV V^{-1}) to mass (kg) and then to water depth (mm) was described in Marek et al. (2006). The load cell signal was composited to 30-min means and the lysimeter mass resolution was 0.01 mm. Daily evapotranspiration (ET) was determined as the difference between lysimeter mass losses and lysimeter gains divided by the lysimeter area (3 m^2). A pump (−10 kPa) provided vacuum drainage and the drainage effluent was weighed by load cells (drainage rate data are not reported here). ET for each 24-h period was divided by 1.02 to adjust the lysimeter area to the midpoint between the two walls (10 mm air gap; 9.5 mm wall thickness; 3.05 m^2 area instead of the inside 3.00 m^2 lysimeter surface area), according to Howell et al. (2004).

2.2. Lysimeter field data

A tall fescue grass (*Festuca arundinacea*) seed brand, Emerald III (Sharp Bros. Seed Co., Healy, KS) was hydro-mulched in the late fall of 2001 on the weather station plot after completing installation of a lysimeter, located in the center of ~1.0 ha, and a subsurface drip irrigation system. The irrigation system used 1.9 L h^{-1} geoflow turbulent flow emitters spaced every 0.46 m along laterals (14 mm ID) placed at 0.15 m depth. The lysimeter had a dense network of lines (64 arranged in a 0.19 m^2 grid) with 3.8 L h^{-1} emitters that allowed 25 mm of water to be applied in 15 min. In 2008, the irrigation system was replaced with a rotary sprinkler system, which used a 3.8 L h^{-1} high pressure pop-up, rotating stream sprinkler spaced every 6.0 m along the laterals. Irrigation was scheduled based on measured daily evapotranspiration (ET) and normally applied at 20–25 mm one to three times a week. Fertilizers (N and P) were applied through the irrigation water. The grass was regularly mowed with a rotary mower and hand-clipped around and on the lysimeter, and the clippings were bagged and removed. The grass height was ~0.1 m after mowing and varied from 0.12 to 0.15 m before mowing.

Cotton and wheat were grown from 2005 to 2008 in crop lysimeter fields, each located in the center of ~1.0 ha, which were used in the determination of Kc (Table 1). Growth and yield of the crops on the lysimeters was comparable to those of the surrounding crops in the field. All field operations were performed with standard 1.0 m wide four row-crop field equipment, except at each lysimeter where hand-cultural methods were applied. Row direction was east to west. Fertility and pest control practices were uniformly applied to the fields. The fields were furrow diked (dike spacing at ~1.5 m) in all years to minimize field runoff and rainfall and irrigation redistribution. Irrigation, equipped with a North-South-aligned sprinkler system, was applied East-West or West-East with a 3-span lateral move sprinkler system from Lindsay Manufacturing Co. (Lindsay, NE). The system was equipped with gooseneck fittings and spray heads (Senninger Super Spray 360E, Clermont, FL) with medium grooved spray plates on drops located ~1.5 m above the ground and 1.0 m apart. The drops could be converted to low energy precision application (LEPA) heads placed ~0.3 m above the ground. The fields were managed under full irrigation, which was scheduled based on measured daily crop water use (ET).

Daily ET measured with the lysimeters was determined as the difference between lysimeter mass losses (evaporation and transpiration) and lysimeter mass gains (irrigation, precipitation,

Table 1
Crops grown at the Texas AgriLife Research—Uvalde for determination of crop coefficient and associated seasonal data.

Crop	Variety[a]	Planting year	Plant-harvest (M/D)	Rainfall (mm)	Irrigation (mm)	ETc (mm)	Temperature		GDD (°C)[b]
							Max (°C)	Min (°C)	
Cotton	DP555	2006	04/12–09/07	75	764	830	35.1	21.5	1846.2
	DP555	2007	04/16–10/18	581	114	689	31.0	20.7	1769.4
Wheat	Ogallala	2005	11/18–05/19	58	435	483	25.3	10.2	1947.2
	Ogallala	2006	11/17–06/06	327	195	485	22.9	10.7	1979.2
	TAM203	2007	11/19–05/21	89	424	505	24.3	9.4	1998.7

[a] DP555 from Delta and Pine Land Co. (Scott, MS), Ogallala from AgriPro COKER (Berthoud, CO), and TAM203 from Texas A&M Univ. (College Station, TX, USA).
[b] GDD, growing degree days, was determined using a base temperature of 15.6 °C for cotton and 0.0 °C for wheat.

or dew) as shown in Fig. 1. Crop coefficient (Kc) was calculated using the Eq. (1). ETo was determined from direct measurement using the lysimeter (Lys ETo) and calculation using the ASCE Penman–Monteith equation (ASCE-EWRI, 2005) for grass (ASCE ETo). Kc curves were fitted to third-order polynomials. Other studies demonstrate that Kc curves can be fitted to third- and up to fifth-order polynomials (Ayars and Hutmacher, 1994; Sammis and Wu, 1985; Stegman, 1988). Lys Kc was the ratio of the lysimeter crop ETc to the grass lysimeter ETo. ASCE Kco was the ratio of the lysimeter ETc to the ASCE computed ETo.

2.3. The ASCE-standardized reference evapotranspiration equation

The ASCE ETo (mm d^{-1}) was estimated using the following formula (ASCE-EWRI, 2005):

$$\mathrm{ETo} = \frac{0.408\Delta(R_n - G) + \gamma(C_n/T + 273)u2(e_s - e_a)}{\Delta + \gamma(1 + C_d u2)} \quad (3)$$

where R_n (MJ m^{-2} d^{-1}) is the measured net irradiance at the crop canopy; G (MJ m^{-1}) is the soil heat flux density; T (°C) is the measured mean daily air temperatures; $u2$ is the mean daily wind speed at 2-m height (m s^{-1}); e_s (kPa) is the saturated vapor pressure; e_a (kPa) is the mean actual vapor pressure; Δ (kPa °C^{-1}) is the slope of the saturation vapor-pressure temperature curve; γ (kPa °C^{-1}) is the psychrometric constant; C_n (K mm s^3 mg^{-1} d^{-1}) is the numerator constant; and, C_d (s m^{-1}) is the denominator constant and both change with crop reference type and calculation time-step. The units for the coefficient 0.408 are m^2 mm MJ^{-1}.

2.4. Statistical analysis

The data were analyzed by paired t-test using PROC TTEST and analysis of correlation using PROC CORR (SAS version 9.1, Cary, NC). These were used to determine statistical differences of the measured lysimeter data from the calculated data. Goodness-of-fit estimators used were p value from the paired t-test. In addition, two statistics were used: (i) root mean square error (RMSE), Eq. (4), (ii) mean relative error (MRE), and (iii) d statistics (Nash and Sutcliffe, 1970), Eq. (5):

$$\mathrm{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{n}(C_i - M_i)^2\right]^{1/2} \quad (4)$$

$$\mathrm{MRE}_i = \frac{1}{n}\sum_{i=1}^{n}\frac{(C_i - M_i)}{M_i}100\% \quad (5)$$

$$d = 1 - \frac{\sum_{i=1}^{n}(C_i - M_i)^2}{\sum_{i=1}^{n}(M_i - M_a)^2} \quad (6)$$

where C_i is the ith calculated value, M_i is the ith measured value, M_{avg} is the averaged measured value, and n is the number of data pairs. d values are equivalent to the coefficient of determination (R^2), if the values fall around a 1:1 line of calculated vs. measured data, but E is generally lower than R^2 when the predictions are biased, and can be negative.

3. Results and discussion

3.1. Cotton

Lysimeter-measured reference evapotranspiration (Lys ETo) over the cotton growing seasons in 2006 and 2007 ranged between 1 and 12 mm d^{-1} (Fig. 2A). During the same periods, crop evapotranspiration (ETc) of cotton ranged between 1 and

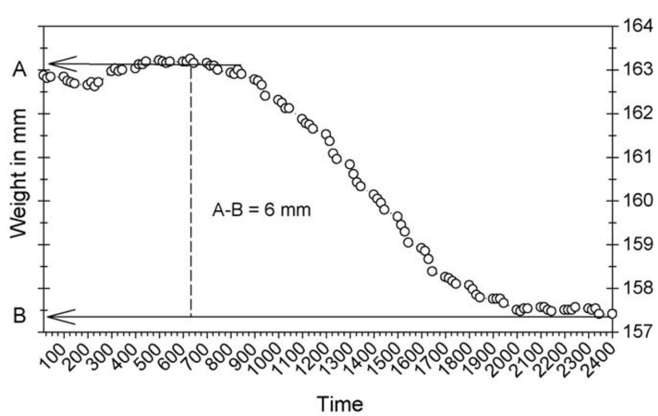

Fig. 1. An example of daily evapotranspiration (ET) determination using a 15-min weighing lysimeter chart. The difference between lysimeter mass losses and lysimeter mass gains represents daily ET.

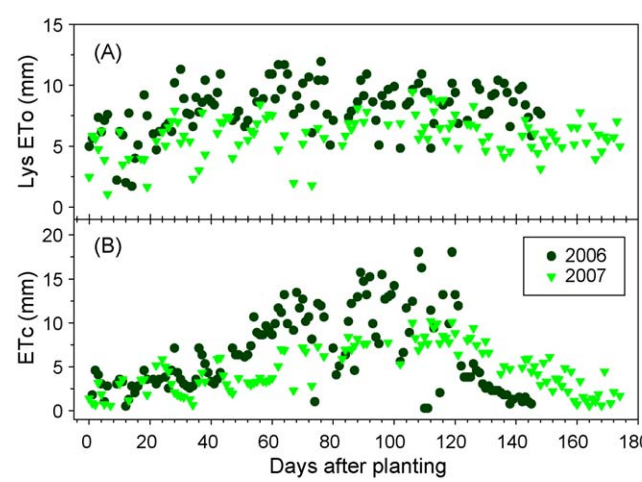

Fig. 2. (A) Lysimeter-measured reference evapotranspiration (Lys ETo) and (B) cotton crop evapotranspiration (ETc) as a function of days after planting for crop growing seasons from 2006 to 2007.

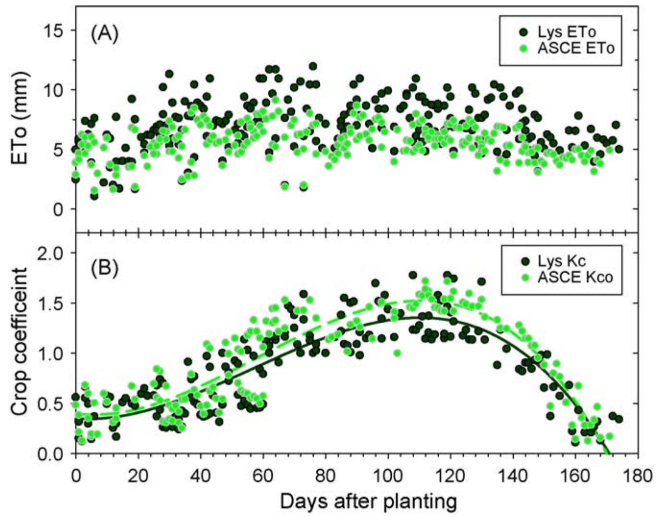

Fig. 3. (A) Lysimeter-measured reference evapotranspiration (Lys ETo) and (B) cotton crop coefficient (Kc) as a function of days after planting for measured Kc using lysimeter (Lys Kc) and calculated Kc based on ASCE Penman–Monteith equation for grass (ASCE Kco). Data were obtained at Texas AgriLife Research Center in Uvalde, Texas in 2006 and 2007. A third polynomial equation for each Kc is as follows:Lys Kc = $0.35 - 2.01 \times 10^{-3} \times \mathrm{DAP} + 2.85 \times 10^{-4} \times \mathrm{DAP}^2 - 1.67 \times 10^{-6} \times \mathrm{DAP}^3$ASCE Kco = $0.40 - 3.80 \times 10^{-3} \times \mathrm{DAP} + 3.45^{-4} \times \mathrm{DAP}^2 - 1.98 \times 10^{-6} \times \mathrm{DAP}^3$

18 mm d^{-1}, reaching the peaks at ~100 d after planting (DAP) in 2006 and ~120 DAP in 2007 (Fig. 2B). Measured maximum ETc approached 15–17 mm d^{-1} and typical maximum daily ETc approached 10–13 mm d^{-1} in 2006 and 7–10 mm d^{-1} in 2007. These values are not greatly different from those (10–12 mm d^{-1}) reported by Howell et al. (2004) at Bushland, Texas. Accumulated cotton ETc was 830 mm in 2006 and 689 mm in 2007, respectively (Table 1). The disagreement in ETc between the 2 years is attributable to lower air temperatures and more frequent rainfalls (consequential higher humilities) in 2007. The present ETc values closely match with those (710 mm in 1998 and 845 mm in 1999) measured using the Parlier lysimeters at San Joaquin valley, California (Grismer, 2002). In comparison with those obtained at Bushland, Texas (Howell et al., 2004), the value in 2006 is larger than, and the value in 2007 is somewhat smaller than their values (739 and 775 mm for full irrigation). Meanwhile, calculated ETo using ASCE Penman–Monteith equation (ASCE ETo) during the crop seasons ranged between 2 and 9 mm d^{-1} and generally underestimated the Lys ETo (Fig. 3A). There was significant difference between the ASCE ETo and the Lys ETo according to a *t*-test ($p < 0.0001$). However, the other evaluation statistics show that the ASCE ETo corresponded to the Lys ETo with root mean square error (RMSE) of 1.20 mm d^{-1}, mean relative error (MRE) of −16.5 %, and *d* value of 0.21 (Fig. 4A). The calculated and measured data also correlated with Pearson's correlation coefficient (r) of 0.84 ($p < 0.0001$).

Cotton crop coefficient (Kc) in the 2 years generally varied from 0.2 to 1.5 for both of lysimeter based Kc (Lys Kc) and ASCE ETo based Kc (ASCE Kco) (Fig. 3B). The ASCE Kco partially overestimated the Lys Kc at ~peaks between 80 and 130 d after planting. A *t*-test shows that the ASCE Kco was significantly different from the Lys Kc ($p < 0.0001$). However, the ASCE Kco matched with the Lys Kc with RMSE of 0.10, MRE of 15.2%, and *d* value of 0.03 (Fig. 4B). The ASCE Kco also correlated with the Lys Kc with r value of 0.97 ($p < 0.0001$). Growth-stage-specific Kc values of cotton were determined based on the separate 2-year Lys Kc curves (Fig. 5). These represent the distribution of Kc over time throughout the season (Wright, 1982). Divisions of the Lys Kc based on crop growth stages show that seasonal variation of Lys Kc

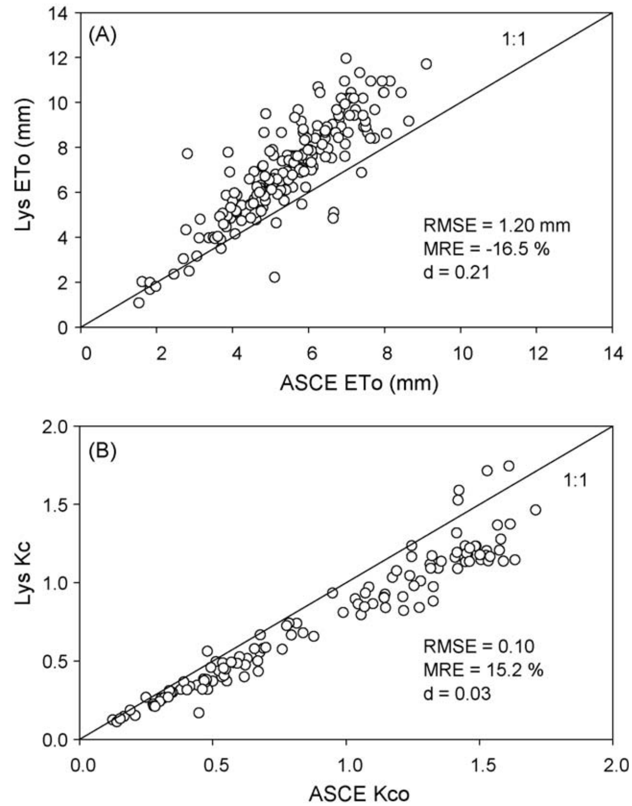

Fig. 4. (A) Lysimeter-measured ETo (Lys ETo) vs. calculated ETo using ASCE Penman–Monteith equation for grass (ASCE ETo) and (B) cotton Kc based on lysimeter measurement (Lys Kc) vs. cotton Kc based on ASCE Penman–Monteith equation for grass (ASCE Kco).

values was small but that of the corresponding growth periods was great between the two crop seasons. Growth-stage-specific Kc for cotton determined was 0.40 at seeding, 1.25 at 25% open boll, and 0.60 at 95% open boll stages (Table 2). The values are slightly larger at initial and mid growth stages than those from FAO-56 (Allen et al., 1998). In addition, our values are generally larger at early and late growth stages than and similar at mid growth stage to those determined at the Texas High Plains (Howell et al., 2004, 2006). They reported ~0.2 at emergence, ~1.2 at first flower, and ~0.8 at first open boll growth stage. Meanwhile, our values generally match with those obtained at the semiarid areas in the USA

Table 2
Cotton crop coefficients (Kc) determined at Uvalde, Texas (A) in comparison to those from Bushland, Texas and from FAO-56 (Allen et al., 1998) (B).

Growth stage	DAP[a]	Kc
(A)		
Seeding	7	0.40
1st square	8–45	0.45
1st bloom	46–65	0.80
Max bloom	66–86	1.08
1st open	87–110	1.23
25% open	111–125	1.25
50% open[b]	126–133	1.05
95% open	134–151	0.60
Pick	152–162	0.10
(B)		
Kc ini	0–30	0.35
Kc mid	80–135	1.15–1.20
Kc end	135–180	0.75–0.35

[a] Days after planting.
[b] The cotton was chemically defoliated.

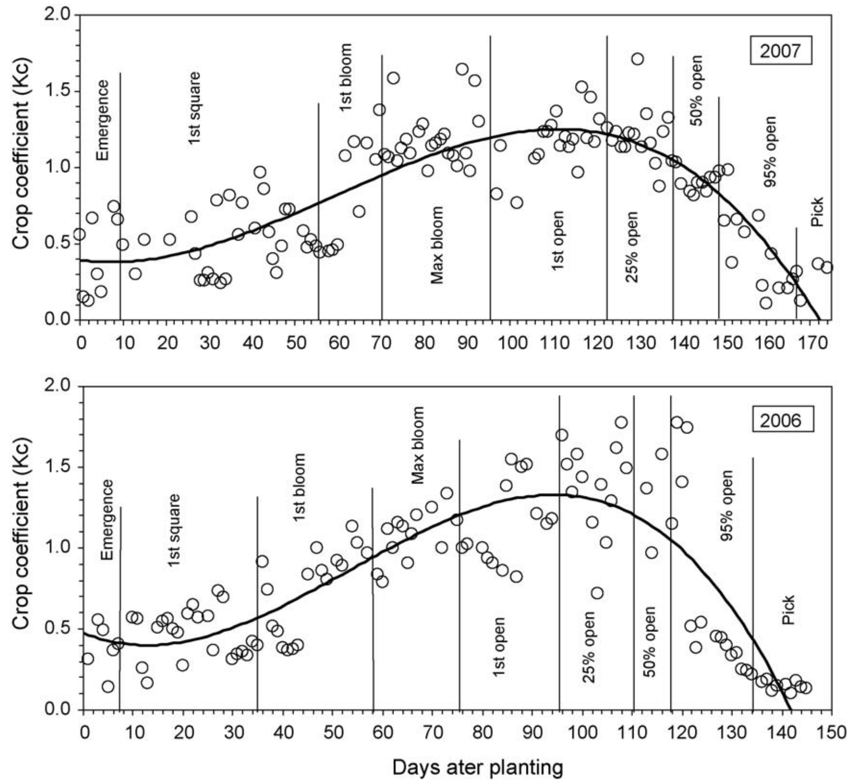

Fig. 5. Growth-stage-specific crop coefficients (Kc) of cotton determined as a function of the days after planting in 2006 and 2007 at Uvalde, Texas. Vertical lines represent growth stages for each year. A third polynomial equation for the Lys Kc is as follows:Lys Kc = $0.35 - 2.01 \times 10^{-3} \times \text{DAP} + 2.85 \times 10^{-4} \times \text{DAP}^2 - 1.67 \times 10^{-6} \times \text{DAP}^3$

(Grismer, 2002; Hunsaker, 1999). At Maricopa, Arizona, the calculated basal crop coefficients (Kcb) ranged from ~0.3 to 1.2 for the early vegetative to effective full cover (Hunsaker, 1999). At Sacramento and San Joaquin valleys, California, the cotton growth-stage Kc values were reported as 0.35 in 0–30 d, 1.15 in 90–150 d, and 0.87 in 150–180 d (Grismer, 2002).

3.2. Wheat

Lys ETo during the wheat growing seasons from 2005 to 2008 generally ranged between 1 and 10 mm (Fig. 6). Seasonal values of wheat ETc varied from 1 to 13 mm d^{-1}, showing the peaks at ~150 DAP in all of the three crop seasons. Comparatively smaller Lys ETo and ETc values during the 2006 season are attributable to lower water demand due to the lower maximum temperature (Table 1). ETc seldom exceeded 1 to 3 mm d^{-1} in winter time, began to accelerate by ~80 DAP, and declined dramatically with senescence after physiological maturity. The values are slightly larger in winter time than, but generally match with those (1–13 mm d^{-1}) reported by Howell et al. (1995b, 1997) at Bushland, Texas. Accumulated ETc range was between 483 and 505 mm (Table 1). These values are considerably smaller than the average value (710 mm) reported by Musick and Porter (1990) and the values (791–957 mm) obtained by Howell et al. (1997) at Bushland, Texas. Our values are also smaller than those (591–624 mm) measured for a spring wheat cultivar at Maricopa, Arizona (Hunsaker et al., 2005). The differences are attributable to the shorter growing seasons (Fig. 6) than those (~290 DAP) at Bushland, Texas and to the smaller daily ETc values in winter times than those (~3–5 mm d^{-1}) at Maricopa, Arizona. In the meantime, ASCE ETo calculated with a range of 1–8 mm d^{-1} slightly underestimated the measured Lys ETo (Fig. 7A). There was significant difference between them according to a *t*-test ($p < 0.0001$) but comparison statistics show that the ASCE ETo was in agreement with the Lys ETo with RMSE of 1.25 mm d^{-1}, MRE of 1.2%, and *d* value of 0.58 (Fig. 8A). The ASCE ETo values also correlated with the Lys ETo values with r value of 0.80 ($p < 0.0001$).

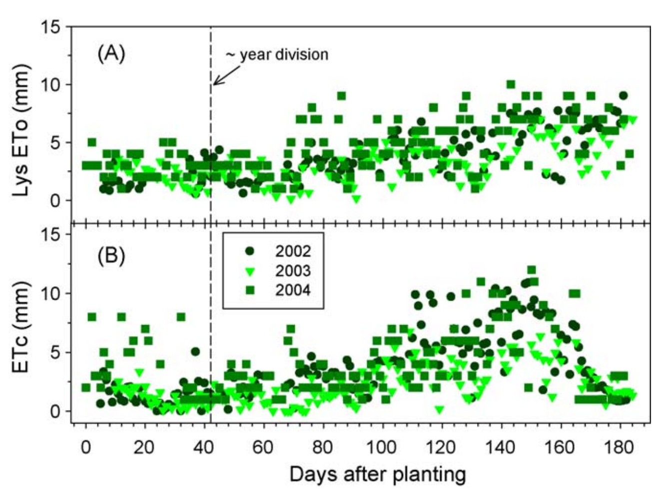

Fig. 6. (A) Lysimeter-measured reference evapotranspiration (Lys ETo) and (B) wheat crop evapotranspiration (ETc) as a function of days after planting for crop growing seasons from 2005 to 2008.

Variation of wheat Kc in the three crop seasons was between 0.1 and 1.7 for both of Lys Kc and ASCE Kco (Fig. 7B). The ASCE Kco over-calculated and was significantly different from the Lys Kc according to a *t*-test ($p < 0.0001$). However, the ASCE Kco agreed with the Lys Kc with RMSE of 0.21, MRE of 21.4%, and *d* value of 0.51 (Fig. 8B). The ASCE Kco also correlated with the Lys Kc with *r* value of 0.82 ($p < 0.0001$). These statistics indicate that the ASCE Kco can be determined with an acceptable accuracy. The measured Lys Kc values showed wide variation but growth stages did not

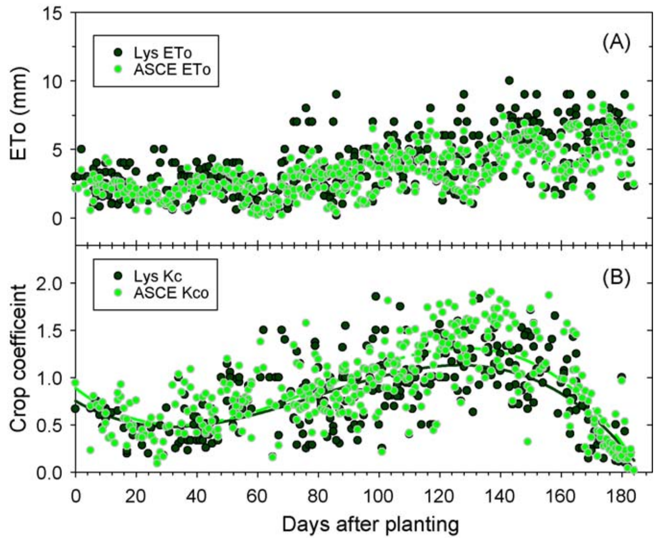

Fig. 7. (A) Lysimeter-measured reference evapotranspiration (Lys ETo) and (B) wheat crop coefficient (Kc) as a function of days after planting for measured Kc using lysimeter (Lys Kc) and calculated Kc based on ASCE Penman–Monteith equation for grass (ASCE Kco). Data were obtained at Texas AgriLife Research Center in Uvalde, Texas from 2005 to 2008. A third polynomial equation for each Kc is as follows: Lys Kc = 0.75 − 0.02 × DAP + 3.66 × 10^{-4} × DAP^2 − 1.54 × 10^{-6} × DAP^{3}ASCE Kco = 0.88 − 0.03 × DAP + 4.71 × 10^{-4} × DAP^2 − 1.94 × 10^{-6} × DAP^3

show much variation among the 3-year crop growing seasons (Fig. 9). Growth-stage-specific Kc values of wheat were also plotted using a third polynomial curve and determined based on divisions of wheat growth stages. The growth-stage-specific Kc was 0.53 at emergence, 1.15 at heading and 0.40 at hard dough (Table 3). The values were smaller at initial growth stage and larger at end growth stage than those from FAO-56 (Allen et al., 1998). In comparison with the Kcb values from the Texas High Plains (Howell et al., 1995b, 2006), our values are slightly larger at early and mid-growth stages than those of ∼0.2 and 0.8–1.0 and similar at late growth stage to that of ∼0.3–0.6. Our values are also larger at early and mid-growth stages and similar at late growth stage to those (1.0 for the peak Kcb) reported at Kimberly, Idaho (Wright, 1982) and nearer to the peak Kcb (1.3) for barley at Davis, California (Jensen et al., 1990).

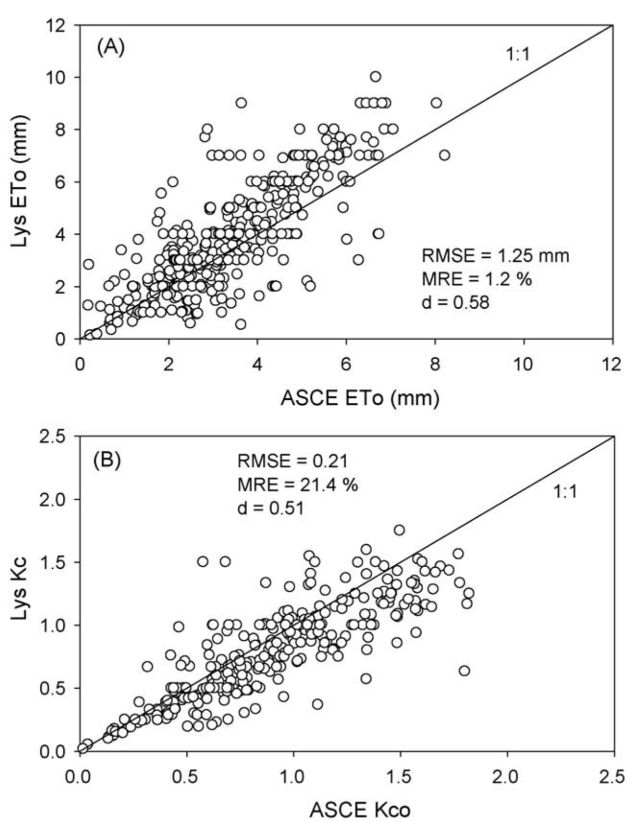

Fig. 8. (A) Lysimeter-measured ETo (Lys ETo) vs. calculated ETo using ASCE Penman–Monteith equation for grass (ASCE ETo) and (B) wheat Kc based on lysimeter measurement (Lys Kc) vs. wheat Kc based on ASCE Penman–Monteith equation for grass (ASCE Kco).

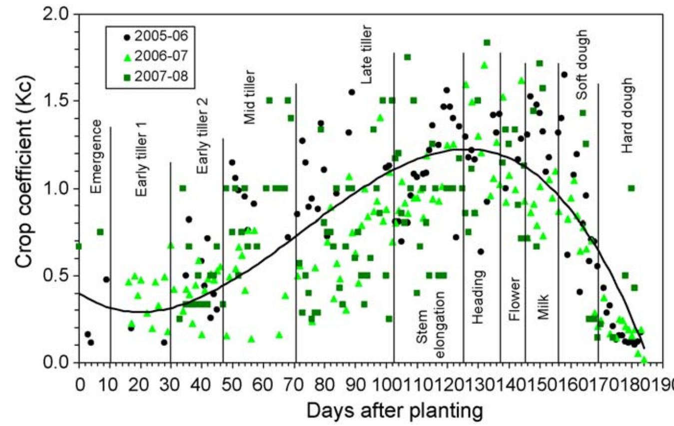

Fig. 9. Growth-stage-specific crop coefficients (Kc) of wheat determined as a function of the days after planting in 2005–06, 2006–07, and 2007–08 at Uvalde, Texas. Vertical lines represent a 3-year-average growth stages. A third polynomial equation for the Lys Kc is as follows: Lys Kc = 0.75 − 0.02 × DAP + 3.66 × 10^{-4} × DAP^2 − 1.54 × 10^{-6} × DAP^3

Table 3
Wheat crop coefficients (Kc) determined at Uvalde, Texas (A) in comparison to those from FAO-56 (Allen et al., 1998) (B).

Growth stage	DAP[a]	Kc
(A)		
Emergence	10	0.53
Early tiller 1	11–31	0.50
Early tiller 2	32–51	0.50
Mid-tiller	52–68	0.70
Late tiller	69–97	0.70
Stem elongation	98–121	1.10
Heading	122–132	1.15
Flowering	133–140	1.10
Milk	141–151	1.00
Soft dough	152–166	0.85
Hard dough	167–183	0.40
(B)		
Kc ini	0–20	0.70
Kc mid	80–150	1.15
Kc end	150–180	0.25

[a] Days after planting.

4. Summary and conclusion

The purpose of this research was to determine plant water usage or crop evapotranspiration (ETc) and crop coefficients (Kc) for cotton and wheat grown in the Wintergarden region of Texas, USA. Irrigation scheduling can then be improved for private consultants and growers to avoid water over use and to more precisely meet the crop water demand to produce greater yields with enhanced water use efficiency. Accumulated ETc estimates for each crop growing season ranged from 689 to 830 mm for cotton and from 483 to 505 mm for wheat. Seasonal Kc values varied from 0.2 to 1.5 for cotton and 0.1 to 1.7 for wheat. Growth-stage-specific Kc values were determined based on the Kc curves that represent the distribution of Kc over time throughout the season (Wright, 1982). Our results showed that Kc values can be different from one region to the other. It is assumed that the different environmental conditions between regions allow variation in variety selection and crop developmental stage which affect Kc (Allen et al., 1998). Crops in South Texas are easily exposed to elevated air temperatures and water vapor pressure deficit over the growing seasons. This can cause temporal and transient leaf stomata closure (Baker et al., 2007; Bruce, 1997; Cornic and Massassi, 1996), impeding plants to transpire at its full potential. The need for regionalized Kc is demonstrated by the comparison between the Kc developed at Uvalde, Texas and those obtained at Bushland, Texas as well as elsewhere in the USA. In the Wintergarden region, the use of Kc developed in other regions will not meet accurate crop water requirement and result in either increased production costs due to over-irrigation or reduced profits due to deficit irrigation. In conclusion the development of regionally based Kc helps tremendously in irrigation management and furthermore provides precise water applications in those areas where high irrigation efficiencies are achieved by center pivot with LEPA (low energy precision application) systems or subsurface drip irrigation.

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